TM-1192
2750.000
April 23, 1983

MEASUREMENT OF CRITICAL TEMPERATURE AS A FUNCTION OF FIELD

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Abstract

The critical temperature has been measured for various magnet conductors as a function of the perpendicular applied magnetic field. The isothermal environment was provided by a variable temperature cryostat which fits into the bore of a 10.0 tesla solenoid. The temperature gradient across the sample volume was measured to be less than 25 millikelvins. The superconducting to normal state transition was measured resistively, using sample current densities from 0.01 to 2 A/cm². The maximum applied magnetic field was 10.0 T and varied less than 0.5% in the sample volume. The critical transport current range of the samples measured was from tens to thousands of amperes in the presence of a 10.0 T perpendicular magnetic field at 4.2K.

Introduction

In the natural evolution of a conductor for a given magnet application, it is desirable to know the shape and magnitude of the critical state surface. This surface, which represents the superconducting to normal transition of the material, is normally measured in isothermal planes of critical current as a function of perpendicular magnetic field. These data represent the intersection of the critical current state surface with the temperature-field plane. Data are also being obtained in the current density-field isothermal planes from 1.65K to 4.5K, but are the subject of another paper at the Applied Superconductivity Conference.[1] The conductors measured here are all multifilamentary solid solution alloys of NbTi, NbTiTa, or the compound Nb_3Sn.

The problem, simply stated, is to determine the maximum temperature where superconducting pairs exist in a given magnetic field. In practice, the transition width is very dependent upon the applied magnetic field and sample.

Experimental Procedure

The samples were prepared for measurement by etching away the copper matrix, except at the current joint and votage tap. A typical sample would range from 0.5 to 1 meter in length and was mounted on a thin G-10 sheet which was in contact with a large copper heat sink (isothermal plane). The sample was in contact with a 1/4 W 100 Ω carbon resistor thermometer. The first resistor is used to control the heater at the top of the copper calorimeter in-between the sample and the control heater and the second was on the G-10 sheet in contact with the sample. The magneto-resistance change in temperature calibration for the various thermometers was measured and taken into account in determination of the sample temperature. The carbon resistors were calibrated and monitored using a standard four terminal network. The absolute temperature resistance was calibrated against a secondary standard from Lake Shore Cryogenics.[2] Then various known temperature points were taken with liquid helium inside the calorimeter. Repetative runs indicated a reproducibility of less than ±25 mK. This process was repeated at various times. In between data points the resistance measurement is checked versus a known standard resistor. The absolute accuracy of the temperature is less than ±30 mK when cross checked with the secondary standard in the experimental set up. The magneto resistance effect on the thermometers was determined by setting a temperature then raising the field taking another reading and then bringing the field back to zero and checking that the temperature had indeed stayed constant during the interval.

Figure 1 is a photograph of the high field variable temperature cryostat. The data are read out by an automatic data logger and then converted from resistance to temperature (uncorrected for magnetic field) by a small computer and printed out versus the sample voltage. A later version will include the field correction term. The long stainless steel vacuum can is a slip fit into a 10.0 T solenoid. A normal experimental run consists of cooling the apparatus to 4.2K, then pumping out the insulation vacuum space (which is at about 3/4 of an atmosphere). The sample thermometer and the surrounding resistors are checked for thermal equilibrium. The sample current is applied and all thermal voltages are determined by reversing this current. The inner calorimeter is then raised to 12K for solid solution or 25K for the compound conductors and the normal resistance is recorded. The temperature of the sample is then reduced until it is superconducting recording sample voltage versus temperature. Then the magnetic field is applied and the process repeated for the new magnetic field.

Data

Data for various high to standard performance NbTi conductors are given in Figures 2 through 5. The data are presented in this form because it is not clear what value should be defined as the true critical temperature at a given magnetic field. There is an excellent discussion of this point in Hawksworth and Larbalestier[3]. Each of the superconducting to normal state transition curves contain 15 to 20 data points at each magnetic field. In general there were two sample runs for each material with the exception of MNT50[4] where only one was available. The multifilamentary nature of the samples however should give additional weight to the typical nature of the measurements.

It should be emphasized that these data were taken resistively. If the same sample is measured inductively the answer will change by a tenth of a degree or so; for example, if the transition of sample MNT50 is measured inductively the normal value is 9.05K for "0" field, or 1/2 height of 8.8K.[5] The resistively determined MNT50 values are given in Table I. The normal and 1/2 height values are 9.38K and 9.3K respectively, therefore indicating that the resistive and inductive values differ by a quarter to half a degree for a given sample.

Summary

In Figure 6 critical temperature is plotted versus magnetic field with the various definitions of temperature shown. The reason for giving the three most commonly used definitions is to enable the reader to combine the data presented here with other data in

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the literature. If the "H_{c2}" data of Berlincourt and Hake[6] at 1.2K; Hawksworth and Larbalestier[3,7] at 4.2K and 2K and those given in Figure 6 are combined, then the critical temperature "$T_c(H)$" at given magnetic field (H) is empirically given by

$$T_c(H) = T_c(0.0)\left(\frac{H_c(0)-H}{H_c(0)}\right)^{1/2}$$

for MNT50 T_c(0 tesla) = 9.35K

H_c(0K) = 15.1 T

If the definition of Tc is taken as the intercept of the transition curve (voltage vrs temperature) to zero volts at a current density of a few amperes/cm^2 or less, then the logical comparison for upper critical field would be the same on the voltage vrs magnetic field curve. The same would apply if the definition were taken to be the half height or fully normal voltage. These points are throughly discussed in reference 3 and need not be covered here.

Acknowledgements

The authors would like to express their appreciation to the following talented people whose help was invaluable: J. Tague, R. Nehring and the rest of the Lab #2 crews under W. Warren and D. Wendt, who kept everything going as the experiment proceeded. The variable temperature cryostat that was used as a model for the one constructed was designed by M. Kuchnir.

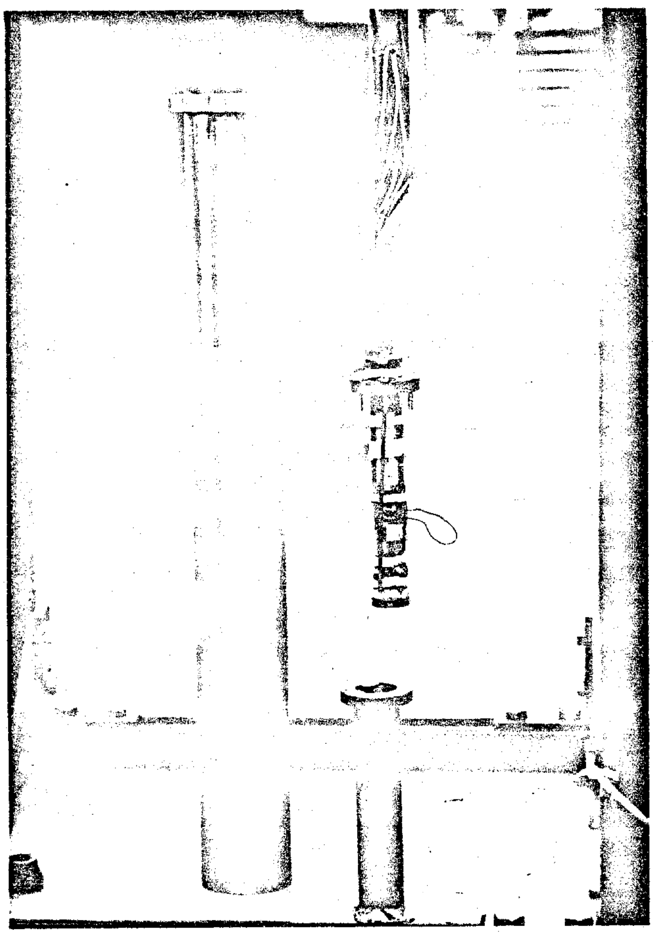

Figure 1. The photograph shows the internal high field Cu-Calorimeter with the vacuum stainless steel jacket standing beside it disassembled. The sample was located in the lower third of the sample holder in thermal contact with its resistor thermometer. The controller resistor was located in the upper third. The temperature gradient between the two was less than 25 mK.

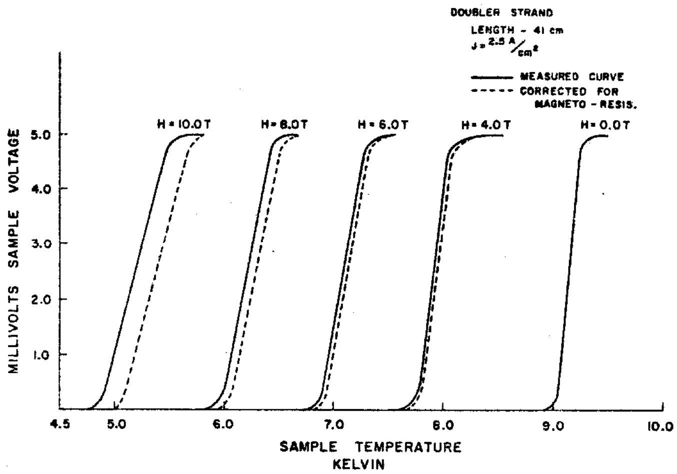

Figure 2. The transition of a typical Energy Saver/Doubler strand, from normal to superconducting state, is shown in the above graph as a function of temperature for different magnetic fields. The material refered to as standard strand is Nb46.5 w/o Ti (std. strd.) in the form of 8 to 10 micron filaments. There have been two separate samples measured and they agreed within the thermometer reproducibility ±25mK.

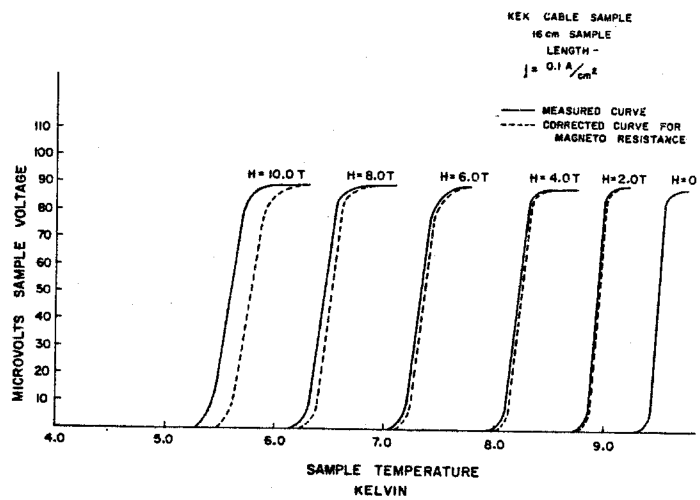

Figure 3. The transition of a Japanese (KEK) monolithic high field (10T) multikiloampere conductor, from normal to superconducting state is shown in the above graph as a function of temperature for different magnetic fields. This material is Nb44 w/oTi alloy with very large 80 micron filaments. There were two different samples taken from the same length of conductor and they agreed within the reproducibility of the thermometer ±25mK.

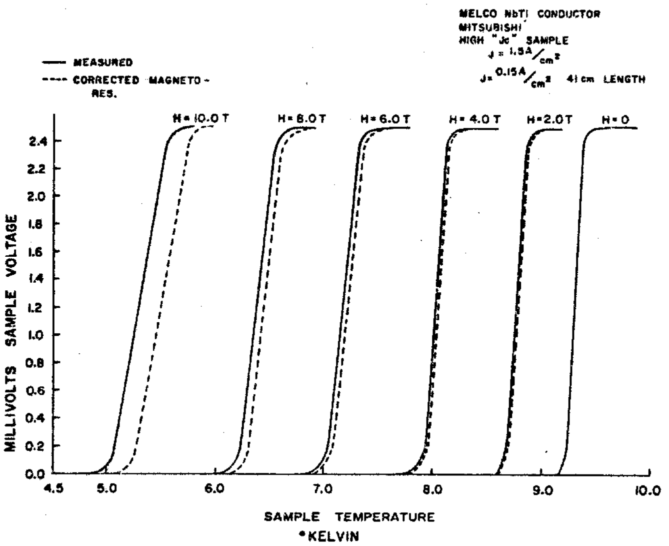

Figure 4. The transition of a Japanese .305 mm diameter very high performance strand binary NbTi conductor (125 kA/cm² at 8 T and 4.2K), from normal to superconducting state is shown in the graph as a function of temperature for different magnetic fields. This material is Nb47w/oTi alloy with 8 micron filaments. Manufacturer's designation is MELCO(MNT 50).

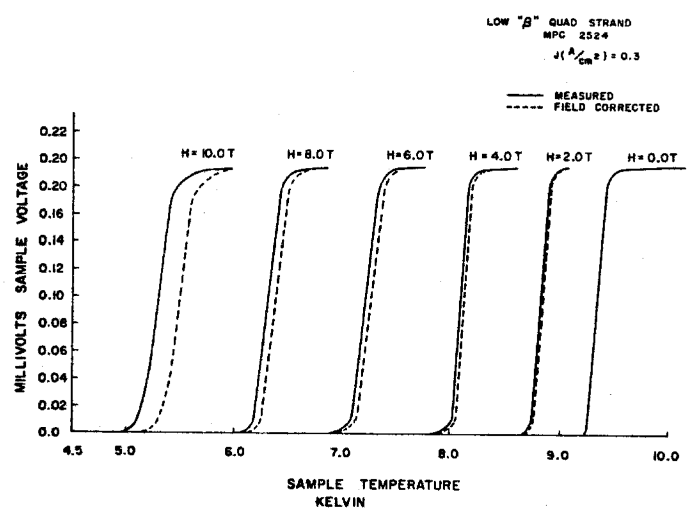

Figure 5. The transition of a very high current density strand from a multikiloampere low "β" quadrupole cable (5.5 kA/turn at 6.5T at 4.2K $10^{-12}\Omega$-cm), from normal to superconducting state is shown in the above graph as a function of temperature at different magnetic fields. This material differs from the standard strand material primarily in metalurgical history and is basically Nb46.5w/oTi (Spc. Strd.) in the form of 20 micron filaments.

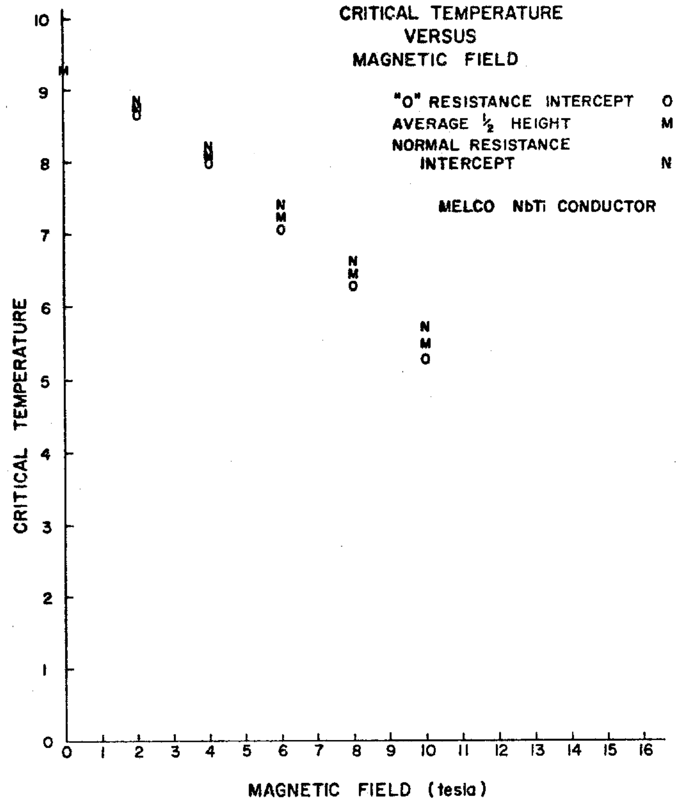

Figure 6. The critical temperature is shown as a function of perpendicular magnetic field for the highest 8 tesla critical current density strand tested at 4.2K. The data is the center of the letters and the temperature error is about 1/2 their vertical size and 0.01 tesla wide. The material is Nb47w/oTi alloy. This is the same sample as shown in Figure 4. The logic for showing three different definitions of critical temperature on the same figure is to enable the reader to use data from other papers for comparison.

TABLE I: T_c Data

°K

Material	"0" O	"0" M	"0" N	"10.0T" O	"10.0T" M	"10.0T" N	Width 10^{-3}K "H" 0	Width 10^{-3}K "H" 10	Width Ratio 10/0
(MNT50)	9.23	9.3	9.38	5.25	5.5	5.78	150	530	3.5
Spc.Strd.	9.25	9.35	9.43	5.33	5.48	5.63	180	300	1.7
KEK Cond.	9.41	9.48	9.55	5.58	5.75	5.83	140	250	1.8
Std.Strd.	9.05	9.15	9.25	5.05	5.38	5.70	200	650	3.3
Nb-Ti-Ta	9.05	9.12	9.2	5.36	5.58	5.81	150	450	3.0
Nb_3Sn	17.71	17.88	18.0	11.99	12.12	12.25	240	260	1.1

* Holec Nb_3Sn 36 filament, 62% copper volume 0.75 mm diameter strand. This is fabricated using Nb tubes packed with Nb_2Sn power cold reduced and then reacted 675°C for 48 hrs.

The columns 0, M, and N are the zero resistance intercept temperature the half height or average temperature between superconducting and fully normal, and then fully resistive temperature respectively. The widths of the transitions are the difference between fully superconducting and normal temperatures. The ratio in the last column of Table I refers to the ratio transition widths at zero field and at 10T applied magnetic field.

Refernces

1. MC-4, 1982 Applied Superconductivity Conference, Knoxville, Tenn.
2. Lake Shore CRYOTRONICS, Inc. Model CGR-1-2000, serial C12Ø1. This resistor has been checked against vapor thermometers periodically, as well as other secondary standards as part of the thermomery used in the Energy/Saver Accelerator at Fermilab.
3. D. G. Hawkworth, D. C. Larabalestier, Adv. Cryo. Engr. 26, 479 (1980).
4. Mitsubishi Electric Company.
5. D. Smathers and D. Larabalestier, Private Communication.
6. T. G. Berlincourt and R. R. Hake, Phys. Rev. Lett. 9, 293 (1962).
7. D. G. Hawksworth, Appendix II, PH.D. Thesis, Univ. of Wisconsin, 1982.
8. MC-5, 1982 Applied Superconductivity Conference, Knoxville, Tenn.